The effects of muscle model and calibration strategy on muscle fatigue estimation

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EXTENDED ABSTRACT

1. Introduction

The determination of muscle forces through computer modeling and simulation is of great interest for estimating loads on bones and joints, with applications in rehabilitation, injury prevention in sports and workplaces, and surgical planning for reconstructing diseased joints [1]. Muscle force capabilities change dynamically over time due to mechanical and physiological variations, such as moment arms, tendon lengths, muscle activation patterns, and muscle fatigue, making their modeling particularly challenging. These parameters are subject-specific and require careful calibration to achieve accurate estimations. Furthermore, more complex muscle models demand the calibration of a greater number of parameters.

Since the estimation of muscle fatigue is directly tied to the forces produced by muscles, and the authors aimed to improve their previous results in estimating dynamic activities [2], the objective of this work is to determine the effect of using different muscle models and calibration strategies to estimate muscle fatigue during short-duration, high-intensity exercises.

2. Material and methods

2.1. Experimental data collection

Six participants (3 males, 3 females) were selected for this study. All were in good health, had no record of upper limb injuries or neuromuscular disorders, and were also required to refrain from consuming caffeinated or alcoholic drinks or exercise 48 h before the study. Each participant provided written informed consent, which was approved by the Research Ethics Committee of La Coruña-Ferrol, before taking part in the study.

2.1.2. Instrumentation and experimental procedures

The HUMAC Norm isokinetic dynamometer was used to measure the joint angle and torque exerted by the subjects in this study. Each participant was placed in a lying position and securely fastened to prevent movement of any joints other than the elbow, as illustrated in Figure 1. Participants were instructed to perform maximal voluntary isometric contractions (MVCs) of elbow flexion with their right arm. The protocol began with isometric calibration measurements taken at different joint angles, followed by isokinetic calibration measurements. After a resting period, participants performed a short-duration, high-intensity isokinetic exercise, which was followed by two isometric MVCs conducted after 1 min and 10 min of rest, respectively.

Figure 1: HUMAC Norm isokinetic dynamometer+.

2.2. Models

The one-degree-of-freedom (elbow flexion/extension) musculoskeletal model (Figure 2) included seven muscles (triceps long, medial, and lateral heads; biceps long and short heads; brachioradialis; and brachialis). The model was adapted from [3], with link lengths scaled to the subject. This model, in combination with the measured joint angle, was used to calculate muscle lengths and default moment arms during the exercises.

Two types of musculotendon models were used for muscle force estimation. The first was a Hill-type musculotendon model, which accounts for physiological force constraints, and the second was a simplified model that does not consider musculotendon actuator dynamics.

Lastly, the four-compartment muscle fatigue model [4] was applied to predict metabolic inhibition during short-duration, high-intensity exercises.

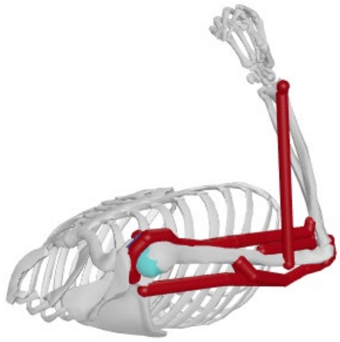

Figure 2: 7-muscle arm model.

2.3. Calibration of muscle parameters

In this study, muscle length parameters were scaled based on the calculated muscle lengths observed during the motion of the model. Maximum muscle isometric force and moment arms were calibrated for both musculotendon models through an optimization process, using the measured torques as a reference. Subsequently, muscle fatigue parameters were fine-tuned to align with the torques experimentally measured during the short-duration, high-intensity exercise.

To assess the impact of calibration on force and muscle fatigue estimation, simulations were also performed using default parameter values.

3. Results

For all the different approaches tested in this study (combinations of default and calibrated muscle parameters, and the two muscle models), the torques produced by the estimated muscle forces were compared with dynamometer readings during MVCs. The root-mean-square error (RMSE) was calculated between measured and simulated results to provide a quantitative analysis. In general, good correlations were obtained. A detailed comparison of the various solutions revealed notable differences, highlighting how variations in the muscle model and its parameters influenced the torque histories of the joint.

4. Discussion and conclusions

The findings of this investigation underscore the significant challenges associated with subject-specific parameter calibration in musculoskeletal modeling. They also provide valuable insights for advancing the estimation of dynamic activities through computer modeling and simulation. By addressing these model and calibration comparisons, the study paves the way for refining existing models and enhancing their capability to predict muscle forces and fatigue during complex activities. These advancements hold considerable promise for applications in rehabilitation, sports science, and ergonomic research.

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